A Remote Field Course Implementing High-Resolution Topography Acquisition ~~and~~**with Geomorphic** Applications ~~Applied to Geomorphology~~

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Abstract

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~~The course "Geoscience Field Issues Using High Resolution Topography to Understand Earth Surface Processes" was originally intended to be conducted in-person with both field data collection and analysis to meet the "field" component of the University of Northern Colorado's Earth Science degrees (Environmental and Geology). With the 2020 world pandemic and cancellation of most in-person activities for 2020, the course was adapted for 100% online implementation with an optional one-day field campaign. To prepare for the changed delivery model, UNAVCO and the University of Northern Colorado collected GNSS data, drone imagery for use in structure from motion, and terrestrial laser scanning from a site near Greeley, Colorado USA on the Cache la Poudre River. These data were used in mock field campaigns and real analyses implemented by students virtually through Zoom and Canvas. The objective of the course is to train students in manual and remote sensing methods of topographic data collection, including 1) GPS/GNSS surveys, 2) structure from motion (SfM), and 3) ground-based (terrestrial laser scanning, TLS) and airborne LiDAR. Course content focused on earth surface process applications, but could be adapted to other applications. This was taught workshop style with the bulk of the instruction and application occurring within a 2 week period during the summer. Students from throughout North America attended the course, most meeting Field Camp requirements required for graduation. Despite the challenging conditions, students met the majority of the National Association of Geoscience Teachers' Field Capstone Learning Outcomes.~~

Here we describe the curriculum and outcomes from a data-intensive geomorphic analysis course: "Geoscience Field Issues Using High-Resolution Topography to Understand Earth Surface Processes," which pivoted to virtual in 2020 due to the COVID-19 pandemic. The curriculum covers technologies for manual and remotely sensed topographic data methods, including: 1) Global Positioning Systems and Global Navigation Satellite System (GPS/GNSS) surveys, 2) structure from motion (SfM) photogrammetry, 3) and ground-based (terrestrial laser scanning; TLS) and airborne lidar. Course content

focuses on earth-surface process applications, but could be adapted for other geoscience disciplines. Many other field courses were cancelled in summer 2020, so this course served a broad range of undergraduate and graduate students in need of a field course as part of degree or research requirements. Resulting curricular materials are available freely within the National Association of Geoscience Teachers' (NAGT's) *Teaching with Online Field Experiences* collection. The authors pre-collected GNSS data, unscrewed-aerial-system- (UAS-) derived photographs, and ground-based lidar, which students then used in course assignments. The course was run over a two-week period and had synchronous and asynchronous components. Students created SfM models that incorporated post-processed GNSS ground control points and created derivative SfM and TLS products including classified point clouds and digital elevation models (DEMs). Students were successfully able to 1) evaluate the appropriateness of a given survey/data approach given site conditions; 2) assess pros and cons of different data collection and postprocessing methods in light of field and time constraints and limitations of each; 3) conduct error and geomorphic change analysis; and 4) propose or implement a protocol to answer a geomorphic question. Overall, our analysis indicates the course had a successful implementation that met student needs as well as course-specific and NAGT learning outcomes, with 91 % of students receiving an A, B, or C grade. Unexpected outcomes of the course included student self-reflection and redirection and classmate support through a daily reflection and discussion post. Challenges included long hours in front of a computer, computing limitations, and burnout because of the condensed nature of the course. Recommended implementation improvements include spreading the course out over a longer period of time or adopting only part of the course and providing appropriate computers and technical assistance. This manuscript and published curricular materials should serve as an implementation and assessment guide for the geoscience community to use in virtual or in-person high-resolution topographic data courses that can be adapted for individual labs or for an entire field or data course.

1 Introduction

1.1 Background on course format and partners

The COVID-19 pandemic forced most higher education courses to ~~remote options~~use virtual delivery modes for part or all of 2020 (Ali, 2020), which posed a challenge for all disciplines. This ~~limitation~~change was particularly challenging for ~~geoscience programs because of their field tradition, with~~the many United States (US) undergraduate geoscience programs ~~requiring,~~ which require field camp or a field course for degree completion (Wilson, 2016). The majority of these field courses ~~were~~had been planned for in-person implementation and were quickly redesigned for remote delivery ~~(most~~. Most US universities closed campuses March 2020 and did not return to in-person until fall 2020 or later; whereas the field courses ~~occurred~~needed to occur May through August 2020~~)~~. In response to this crisis, geoscience field instructors worked together with the National Association of Geoscience Teachers (NAGT) to develop and share remote field teaching resources through the *Designing Remote Field Experiences* project (Egger et al., 2021).

This manuscript describes one such ~~impacted~~ course ~~that pivoted to remote teaching~~, "Using High-Resolution Topography to Understand Earth Surface Processes," ~~which~~taught through the University of Northern Colorado (UNC). It was originally planned ~~to teach terrestrial laser scanning (TLS) and structure~~as an in-person course with Structure from ~~motion~~Motion photogrammetry (SfM~~)~~), Terrestrial Laser Scanning (TLS), and Global Navigation Satellite System (GNSS)[1] data collection and analysis applied to geomorphic issues in a mixed field/classroom setting. The course implementation and curriculum were adjusted ~~so that~~to a remote delivery mode by collecting TLS, GNSS, and ~~drone~~uncrewed aerial system (UAS) imagery for SfM ~~were collected~~ prior to the ~~field~~ course start. Informational videos about the field site and data collection were also provided to the students~~in addition to the pre-collected data for use in the course curriculum.~~. The ~~needed~~ data were collected near Greeley, Colorado on the Cache la Poudre River by Bywater-Reyes from the University of Northern Colorado, in collaboration with UNAVCO (unavco.org~~), near Greeley, Colorado on the Cache la Poudre River.~~). Other geomorphic datasets were drawn from UNAVCO and OpenTopography (https://opentopography.org/) archives. The class had 23 students total (16 undergraduates and 7 graduate students).

~~This course, and the activities it included, were contributed to the National Association of Geoscience Teachers (NAGT; nagt.org) Designing Remote Field Experiences Collection. At the outset of the pandemic, NAGT and partners recognized the critical need for community collaboration on making the transition to remote field teaching and supported an initiative to crowd source curriculum development. The resulting activities and courses, including the one described in this paper, were compiled on the NAGT website (https://nagt.org/nagt/teaching_resources/field/designing_remote_field_experie.html). The overall course is at https://serc.carleton.edu/NAGTWorkshops/online_field/courses/240348.html and the individual activities were linked within the course page as well as being contributed individually to the Online Field Teaching Activities collection (https://serc.carleton.edu/NAGTWorkshops/online_field/courses/240348.html).~~

~~The objective of the course was for students to learn manual and remote sensing methods of topographic data collection, including 1) GPS/GNSS, 2) structure from motion (SfM), and 3) ground-based (terrestrial laser scanning, TLS) surveying and airborne LiDAR use.~~ Bywater-Reyes was the primary course designer and instructor for the course and led the adjustments to remote teaching. ~~Course content focused on earth-surface process applications, but could be adapted to other geoscience topics. The course was taught workshop style with the bulk of the instruction occurring within a 2-week period during the summer. Synchronous lectures were conducted via Zoom and course content distributed via Canvas. Several students attended an optional in-person field collection campaign. The course culminated in a final project where students were able to explore the Poudre River data or another data set of their choosing.~~

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[1] GNSS (Global Navigation Satellite System) is the general term that refers to all Earth's satellite navigation systems. Most people are more familiar with the term GPS (Global Positioning System), which technically, refers to only the US satellite constellation. Hereafter this paper will refer to GNSS or GPS/GNSS.

UNAVCO runs the National Science Foundation (NSF) and National Aeronautics and Space Administration (NASA) geodetic facility (GAGE: Geodetic Facility for the Advancement of Geoscience). ~~As such, its primary~~Its mission ~~is to support geodesy data collection and research, but it also provides~~includes providing educational support ~~(including data acquisition, short courses, and curriculum)~~ to the broader geodesy and geoscience communities~~.~~; thus, UNAVCO staff collaborated on the prepared data collection. The teaching activities developed for this course were adapted from UNAVCO's~~-~~ GEodesy Tools for Societal Issues (GETSI; https://serc.carleton.edu/getsi/index.html) modules: Analyzing High Resolution Topography with TLS and SfM (https://serc.carleton.edu/getsi/teaching_materials/high-rez-topo/index.html) and High Precision Positioning with Static and Kinematic GPS/GNSS (https://serc.carleton.edu/getsi/teaching_materials/high-precision/index.html)

This course, and the activities it included, were contributed to the NAGT *Designing Remote Field Experiences* collection (https://serc.carleton.edu/NAGTWorkshops/online_field/index.html) (Egger et al., 2021). The overall course is at https://serc.carleton.edu/NAGTWorkshops/online_field/courses/240348.html and the individual activities are linked within the course page, as well as being contributed individually to the *Online Field Teaching Activities* collection (https://serc.carleton.edu/NAGTWorkshops/online_field/index.html).

1.2 Value of course topic

High-resolution topographic datasets (SfM and ground-based and airborne lidar) are valuable in disciplines ranging from geomorphology and tectonics to engineering and construction (Bemis et al., 2014; Passalacqua et al., 2015; Robinson et al., 2017; Tarolli, 2014; Westoby et al., 2012). Use of high-resolution data in Earth Science education allows students to quantify landscapes and their change at sub-meter resolution (Pratt-Sitaula et al., 2017; Robinson et al., 2017). Understanding surface processes is listed as very important in the recent "Vision of Change in the Geosciences" with the objective "Students will be able to recognize key surface processes and their connection to geological features and possible natural and man-made hazards" (Mosher et al., 2021, p. 17). Furthermore, use of multiple types of data allows students to practise critical thinking skills such as assessing which acquisition method is appropriate for different scenarios and what errors are associated with different methods. Critical thinking, integrating diverse data sources, and strong quantitative skills were all identified as very important skills for undergraduate students to master (e.g., Kober, 2015). Similarly, making inferences about the Earth system; making spatial and temporal interpretations; working with uncertainty; and developing field, GIS, computational, and data skills were all listed as very important skills for geoscience students to demonstrate (Mosher et al., 2021). Furthermore, learning to collect, post-process, and analyse large datasets is a marketable transferable skill that prepares students for the job market, with cartography and photogrammetry job prospects being "excellent" according to the Bureau of Labor Statistics. For historically minoritized students, high-paying job prospects are particularly important (O'Connell and Holmes, 2011).

1.3 Value of remote learning to removing barriers

Fieldwork, while ~~critical~~valuable to building students' self-efficacy and problem-solving skills (Elkins and Elkins, 2007), can pose a barrier to diversifying the geosciences because of ableism ~~(Carabajal et al., 2020), cost~~ (Carabajal and Atchison, 2020), cost (Abeyta et al., 2020), cultural factors (Hughes, 2015), racism (Abbott, 2006), and sexism (Fairchild et al., 2021) in the field. COVID-19 forced the geosciences to develop virtual field experiences, with a positive side effect of removing many of the aforementioned barriers to fieldwork completion. ~~This course still allowed students to experience many of the positive affective factors incurred during field courses. This course was also the most diverse major's course the instructor, Bywater-Reyes, has ever taught with 24 % (out of 25 students) under-represented minorities and 56 % female students. Students also came from diverse geographic regions, with students from six US states, one US territory, and one international student. At least 40 % of students needed the course to meet degree requirements and most of the eight graduate students needed the expertise for their graduate research.~~For example, the computer-based nature of remote field learning removes many physical accessibility issues present for typical field courses. The option to learn from home may make the remote courses more feasible for students with family or work responsibilities, as well as reduce real and perceived safety issues related to gender, sexual orientation, and race that may occur in tradition field camp settings. Although remote field courses are not necessarily the most desirable for all students, the development of high quality remote field options can be one component of diversifying the geosciences (Egger et al., 2021).

~~1.1 Value of~~2 Course ~~Topic~~

~~High-resolution topographic datasets (structure from motion~~overview **and** ~~ground-based and airborne lidar) are increasing useful for disciplines ranging from geomorphology, tectonics, to engineering and construction (Bemis et al., 2014; Passalacqua et al., 2015; Robinson et al., 2017; Tarolli, 2014; Westoby et al., 2012). Use of high-resolution data in Earth Science education allows students to quantify landscapes and their change at submeter resolution (Pratt-Sitaula et al., 2017; Robinson et al., 2017). Understanding surface processes is listed as very important in the recent "Vision of Change in the Geosciences" with the objective "Students will be able to recognize key surface processes and their connection to geological features and possible natural and man-made hazards (Mosher et al., 2021)." Furthermore, use of multiple types of data allow students to practice critical thinking skills such as which acquisition method is appropriate for difference scenarios and what errors are associated with different methods. Critical thinking, integrating diverse sources, and strong quantitative skills were all identified as very important skills for undergraduate geoscience students to master. Similarly, making inferences about the Earth system; making spatial and temporal interpretations; working with uncertainty; and developing field, GIS, computational, and data skills were all listed as very important geoscience skills for geoscience students to demonstrate (Mosher et al., 2021). Furthermore, learning to collect, post-process, and analyse large datasets is a marketable transferable skill that prepares students for the job~~

~~market, with cartography and photogrammetry job prospects being "excellent" according to the Bureau of Labor Statistics. For historically marginalized~~learning outcomes ~~students, high paying job prospects are particularly important (O'Connell and Holmes, 2011).~~

~~**1.2 Overview of Modules and Learning Objectives**~~

~~As part of the NAGT Teaching with Online Field Experiences collection, this curriculum attempts to meet as many of the student learning outcomes, developed during the NAGT planning workshop (https://serc.carleton.edu/NAGTWorkshops/online_field/learning_outcomes.html), as possible. The outcomes met are *italicized*.~~

~~By the end of a capstone field experience, whether that experience is online or in-person, students should be able to:~~

- ~~1. Design a field strategy to collect or select data in order to answer a geologic question.~~
- ~~1. Collect accurate and sufficient data on field relationships and record these using disciplinary conventions (field notes, map symbols, etc.).~~
- ~~1. Synthesize geologic data and integrate with core concepts and skills into a cohesive spatial and temporal scientific interpretation.~~
- ~~1. Interpret earth systems and past/current/future processes using multiple lines of spatially distributed evidence.~~
- ~~1. Develop an argument that is consistent with available evidence and uncertainty.~~
- ~~1. Communicate clearly using written, verbal, and/or visual media (e.g., maps, cross-sections, reports) with discipline-specific terminology appropriate to your audience.~~
- ~~1. Work effectively independently and collaboratively (e.g., commitment, reliability, leadership, open for advice, channels of communication, supportive, inclusive).~~
- ~~1. Reflect on personal strengths and challenges (e.g. in study design, safety, time management, independent and collaborative work).~~
- ~~1. Demonstrate behaviors expected of professional geoscientists (e.g., time management, work preparation, collegiality, health and safety, ethics).~~

2.1 Course objectives and geodetic methods

The ~~specific learning outcomes for the course were, after completion~~objective of the course~~,~~ was for students ~~should be able~~ to~~:~~

- ~~A. Make necessary calculations to determine the optimal survey parameters and survey design based on site and available time.~~

- A. Integrate GNSS targets with learn manual and remote sensing methods of topographic data collection, including 1) GPS/GNSS, 2) SfM, and 3) TLS surveying and airborne lidar use. GNSS uses ground-based LiDAR and SfM workflows to conduct a geodetic survey.
- A. Process raw point cloud data and transform a point cloud into a digital elevation model (DEM).
- A. Conduct an appropriate geomorphic analysis, such as geomorphic change detection.
- A. Justify which survey tools and techniques are most appropriate for a scientific question.

The course was organized according to the following daily schedule and units:

Unit 1: Structure receivers to trilaterate positions calculated from **Motion (SfM) and GNSS**

- Day 1 - Getting started with Structure from Motion (SfM) photogrammetry (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/238996.html)
- Day 2 - Introduction to GPS/GNSS
  - o Unit 1: GPS/GNSS Fundamentals (https://serc.carleton.edu/getsi/teaching_materials/high-precision/unit1.html) - from the GETSI module *High Precision Positioning with Static and Kinematic GPS/GNSS* (https://serc.carleton.edu/getsi/teaching_materials/high-precision/index.html)
    - • GPS/GNSS presentation https://d32ogoqmya1dw8.cloudfront.net/files/NAGTWorkshops/online_field/activities/gnss_lecture_presentation.pptx)
    - • GETSI's Accuracy & Precision exercise (https://serc.carleton.edu/getsi/teaching_materials/high-precision/unit1.html#prepared)
  - o Post-processing GPS/GNSS Base Station Position (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/239147.html)
- Day 3 - SfM of Poudre River at Sheep Draw Reach
  - o Ground Control Points for Structure from Motion Activity (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/239349.html)
  - o Structure from Motion for Analysis signals sent by orbiting satellites (to accuracies of River Characteristics Activity (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/239350.html)
- Day 4 - Working with Point Clouds a couple centimetres in CloudCompare and Classifying with CANUPO (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/240357.html)
- Day 5 - Report 1 - SfM Feasibility Report assignment (https://d32ogoqmya1dw8.cloudfront.net/files/NAGTWorkshops/online_field/courses/sfm_feasibility_report.v2.docx)

- Day 6 - Optional Field Day (collected additional SfM dataset with local students who could participate) - no associated assignment

Unit 2: Lidar data (ground-based and airborne), point cloud versus raster forms, and difference detection
- Day 7 - Intro Terrestrial Laser Scanning (TLS; ground-based lidar) (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/241028.html)
- Day 8 - Point Cloud/Raster Differencing and Change Detection
    - Morning activity with course-collected SfM and TLS data - Point Cloud and Raster Change Detection (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/241083.html)
    - Afternoon activity with regional LiDAR from Colorado 2013 floods - DEM of Difference (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/241138.html)
- Day 9 - Airborne LiDAR and additional data sources (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/241410.html)
- Day 10 - Report 2 - Methods Comparison Report or report on their particular interest/research (https://d32ogoqmya1dw8.cloudfront.net/files/NAGTWorkshops/online_field/courses/methods_comparison_report.docx)
- Day 11 - Presentations - students gave short presentations to the group based on their final report

2 Unit 1: Structure from Motion (SfM) and GNSS

On the first day of the course, students were introduced to Structure from Motion (SfM) as a means to create a high-resolution three-dimensional model. Students were also introduced to the concept of ground control for georeferencing the associated model. this use case). SfM is a photogrammetric technique that uses overlapping images to construct three-dimensional models with widespread research applications in geodesy, geomorphology, structural geology, and other sub-fields of geology (Passalacqua et al., 2015; Westoby et al., 2012). SfM can be collected from a handheld camera or an airborne platform such as an aircraft, tethered balloon, kite, or UAS (unmanned aerial system). SfM requires less expensive equipment and less field time, but more processing time, than Terrestrial Laser Scanning (TLS; ground-based lidar). Ground control points are key to both georeferenced the model and reduce subfields in the geosciences (Passalacqua et al., 2015; Westoby et al., 2012). Lidar also generates three-dimensional models valuable for the same range of applications; but it uses laser scanners to send out thousands of laser pulses per second, measure the return time, and calculate distances. Scanners can be ground-based (TLS) or airborne. SfM requires less expensive equipment and less field time, but more processing time, than TLS. In low-vegetation field areas, SfM can yield similarly valuable high-resolution topographic models with point densities usually hundreds of points per square metre (depending on instrument-to-object distance; Westoby et al., 2012); however, TLS is much more

effective in areas with dense vegetation. For both methods, ground control points (GCP), usually measured with GNSS, are needed for georeferencing the topographic model. For SfM, they are also critical for reducing distortions and errors (James et al., 2019). In low vegetation field areas, it can yield a similarly valuable high resolution topographic model applicable to a variety of geologic research questions. The resolution can be similar to TLS, with point densities usually hundreds of points per square meter (depending on camera to object distance; Westoby et al., 2012). One of the key outcomes for students was to understand the benefits and challenges of each method and how to determine the most valuable in different circumstances.

2.1 Day 1: Getting started with Structure from Motion (SfM) photogrammetry

On Day 1, students were introduced to SfM through an introductory presentation (Pratt-Sitaula, "Getting started with Structure from Motion (SfM) photogrammetry"; https://serc.carleton.edu/NAGTWorkshops/online_field/activities/238996.html). Then, students used a camera such as on their smart phone and took overlapping photos of an object of interest. Using a compass bearing, inclination, and distance between ground control, students collected ground control coordinates (relative local coordinate system) to georeference their model. Students used Agisoft MetaShape software to post-process their photos and create the 3D point cloud. Students then evaluated the performance of their model by considering what went well and what might improve their product. Students also made recommendations for how SfM could be applied in the geosciences. An example student product (Figure 1) shows a successful model with annotations showing limitations and quality of the data. Teaching materials for this activity are published here: https://serc.carleton.edu/NAGTWorkshops/online_field/activities/238996.html. The assessment for this activity showed students' mastery in their modeling, with an average of 91%.

2.2 Day 3: Introduction to GPS/GNSS and the Cache la Poudre Site

2.2.1 Introduction to GPS/GNSS

In the Day 1 activity, students used a relative local coordinate system to have a to-scale model. However, for real world applications an absolute coordinate system is frequently preferable. As such, methods such as survey-grade Global Positioning Systems (GPS; US system) or more generally, Global Navigation Satellite System (GNSS), yield appropriate globally georeferenced ground control. As such, the GETSI module *High Precision Positioning with Static and Kinematic GPS/GNSS* was adapted by introducing students to appropriate methods in a lecture followed by a series of hands on activities. In the morning of Day 2, students completed an activity comparing the accuracy and precision of various GNSS collection methods with using the module's *Unit 1: GPS/GNSS Fundamentals Accuracy and Precision* (Crosby and Lauer; https://serc.carleton.edu/getsi/teaching_materials/high_precision/unit1.html#prepared). Assessment included a concept sketch of GNSS systems (Figure 2) and quantification and evaluation of accuracy and precision of different grades of GNSS and recommendations for appropriate applications of each. Students mastered these tasks, with course assessments of 88% and 85%, respectively.

~~2.2.2 Introduction to Cache la Poudre Field Site~~ 2.2 Course delivery

~~In the afternoon of Day 2, students were introduced to the field site and methods used for data collection at the Cache la Poudre field location. The UNAVCO-UNC team had visited~~ Course content focused on earth-surface process applications, but could be adapted to other geoscience topics. The course was taught workshop style, composed of multiple synchronous work sessions with asynchronous work time in between. The bulk of the instruction occurred within a 2-week period during the summer. Synchronous lectures were conducted via Zoom and course content distributed via Canvas. The class used Slack as an asynchronous way to exchange questions, comments, and solutions amongst the students and between the students and instructor. During the course, students worked with three different analytical software packages: Agisoft MetaShape, CloudCompare, and ArcGIS Map. Five students attended an optional in-person field collection campaign (one student travelled from out-of-state and the remainder were UNC students). The course was divided into two units: Unit 1 focused on the SfM workflow, including integrating GNSS and point cloud processing; and Unit 2 on lidar products and workflows, including TLS, topographic differencing, airborne lidar, and methods comparison. Each unit ended in a unit report, with the second providing students an opportunity to improve workflows and explore additional data sources and analyses.

2.3 Learning outcomes

The course-specific learning outcomes were, students should be able to:
   A.   Make necessary calculations to determine the optimal survey parameters and survey design based on site and available time.
   B.   Integrate GNSS targets with ground-based lidar and SfM workflows to conduct a geodetic survey.
   C.   Process raw point cloud data and transform a point cloud into a digital elevation model (DEM).
   D.   Conduct an appropriate geomorphic analysis, such as geomorphic change detection.
   E.   Justify which survey tools and techniques are most appropriate for a scientific question.

The course activities also helped students meet many of the NAGT Capstone Field Experience Learning Outcomes. These nine outcomes were developed by a group of 32 experienced field educators, who came together in spring 2020 to develop comprehensive learning outcomes for field experiences that are relevant to both in-person or online delivery modes (https://serc.carleton.edu/NAGTWorkshops/online_field/learning_outcomes.html). By the end of a capstone field experience, whether that experience is online or in-person, students should be able to:
   1.   Design a field strategy to collect or select data in order to answer a geologic question.
   2.   Collect accurate and sufficient data on field relationships and record these using disciplinary conventions (field notes, map symbols, etc.).

3. Synthesize geologic data and integrate with core concepts and skills into a cohesive spatial and temporal scientific interpretation.

4. Interpret earth systems and past/current/future processes using multiple lines of spatially distributed evidence.

5. Develop an argument that is consistent with available evidence and uncertainty.

6. Communicate clearly using written, verbal, and/or visual media (e.g., maps, cross-sections, reports) with discipline-specific terminology appropriate to your audience.

7. Work effectively independently and collaboratively (e.g., commitment, reliability, leadership, open for advice, channels of communication, supportive, inclusive).

8. Reflect on personal strengths and challenges (e.g. in study design, safety, time management, independent and collaborative work).

9. Demonstrate behaviors expected of professional geoscientists (e.g., time management, work preparation, collegiality, health and safety, ethics).

Table 1 shows the alignment between the daily activities and course-specific and NAGT learning outcomes. It also provides links to the activity pages within the NAGT *Online Field Teaching Activities* collection.

Table 1. Activities by day and alignment with course-specific and NAGT learning outcomes.

Activity	Course-specific learning outcomes	NAGT capstone field learning outcomes
Course Unit 1: SfM and GPS/GNSS Day 1 - Getting started with Structure from Motion (SfM) photogrammetry (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/238996.html)	A. Survey design C. Point cloud and DEM	1, 2, 7
Day 2a - GPS/GNSS Fundamentals (https://serc.carleton.edu/getsi/teaching_materials/high-precision/unit1.html)	A. Survey design B. GNSS and geodetic survey E. Justify tools/techniques	1
Day 2b - Post-processing GPS/GNSS Base Station Position (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/239147.html)	B. GNSS and geodetic survey	1
Day 3a - Ground Control Points for Structure from Motion Activity (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/239349.html)	A. Survey design B. GNSS and geodetic survey	1-5, 7, 9

Day 3b - Structure from Motion for Analysis of River Characteristics Activity (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/239350.html)	C. Point cloud and DEM D. Geomorphic analysis	1-5
Day 4 - Working with Point Clouds in CloudCompare and Classifying with CANUPO (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/240357.html)	C. Point cloud and DEM D. Geomorphic analysis E. Justify tools and techniques	3-5
Day 5 - SfM Feasibility Report assignment (https://d32ogoqmya1dw8.cloudfront.net/files/NAGTWorkshops/online_field/courses/sfm_feasibility_report.v2.docx)	A. Survey design B. GNSS and geodetic survey C. Point cloud and DEM D. Geomorphic analysis E. Justify tools/techniques	3-6
Day 6 - Optional field day	B. GNSS and geodetic survey	1, 7, 9
Course Unit 2: TLS, Topographic Differencing, and Method Comparison Day 7 - Introduction to Terrestrial Laser Scanning (TLS) (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/241028.html)	C. Point cloud and DEM (E. Justify tools/techniques)	3-7, 9
Day 8a - Point Cloud and Raster Change Detection (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/241083.html)	C. Point cloud and DEM E. Justify tools/techniques	3-7, 9
Day 8b - DEM of Difference (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/241138.html)	C. Point cloud and DEM D. Geomorphic analysis	3-7, 9
Day 9 - OpenTopography Data Sources and Topographic Differencing (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/241410.html)	C. Point cloud and DEM D. Geomorphic analysis	3-6, 9
Day 10 - Methods Comparison Report (https://d32ogoqmya1dw8.cloudfront.net/files/NAGTWorkshops/online_field/courses/methods_comparison_report.docx)	A. Survey design C. Point cloud and DEM D. Geomorphic analysis E. Justify tools/techniques	3-6

Day 11 - Presentations	D. Geomorphic analysis E. Justify tools/techniques	6-7, 9

2.4 Field site and prepared data

The course field site was the Cache la Poudre River at Sheep Draw Open Space (City of Greeley Natural Areas) in northern Colorado ~~some weeks earlier in order to collect the data.~~. It was selected because: 1) the site shows both standard river features and evidence of extreme flooding; 2) the Poudre River is important to several local communities; and 3) the site is proximal to the UNC campus. According to the Coalition for the Poudre River Watershed, "The Cache la Poudre River Watershed drains approximately 1,056 square miles above the canyon mouth west of Fort Collins, Colorado. The watershed supports the Front Range cities of Fort Collins, Greeley, Timnath and Windsor. In an average year, the watershed produces approximately 274,000 acre feet of water. More than 80 percent of the production occurs during the peak snowmelt months of April through July" ~~(https://www.poudrewatershed.org/cache-la-poudre-watershed).~~ (https://www.poudrewatershed.org/cache-la-poudre-watershed). In 2013, the Front Range and plains of Colorado experienced extensive flooding. The region received the average annual rainfall in one week (Gochis et al., 2015). There was extensive damage to infrastructure and in some cases the erosion of a 1000-years' worth of weathered material (Anderson et al., 2015). Near Greeley, significant portions of the Poudre trail were impacted as the river topped its floodplain and eroded its banks. The study site is adjacent to the Poudre Trail, with portions of the former trail eroded into the river and the current trail rerouted around the 2013-developed river course.

~~The~~

Data for student use was collected from the Poudre River by a joint UNAVCO-UNC team ~~collected~~ in May 2020. The types of data included were:

- UAS-collected photographs for SfM point cloud generation (DJI Mavic 2 Pro)
- Point clouds collected using TLS (Riegl VZ400)
- Several hours of GNSS base station data (Septentrio Altus APS3G)
- GNSS-measured ground control points locations for georeferencing both SfM and TLS surveys (Septentrio Altus APS3G)
- Videos of field site and field methods

3 Methods

This course was developed and implemented in response to the COVID-19 pandemic and the need for students to fulfil degree requirements and not designed as an educational research study before implementation. Thus, there are inherent limitations to

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the available data and conclusions that can be drawn from the project. Nonetheless, there is value in sharing this robust open-source curriculum, describing how the course was implemented, and outlining how student learning outcomes were assessed and achieved. This study went through the Institutional Review Board at University of Northern Colorado, which determined this project to be exempt under 45 CFR 46.104(d)(704) for research, Category 4. Therefore, course artefacts and student demographic data can be used in research so long as no identifying information is revealed. Student artefacts included submitted assignments, unit reports, posts from a daily Slack discussion forum and unsolicited feedback given directly to the instructor. We extracted examples from artefacts and associated assessments to illustrate students' accomplishments and evaluate whether the course, and to a lesser extent, NAGT capstone field learning outcomes were met. We describe Course Implementation and Assessment Approach in Section 4, and alignment with course-specific (5.1) and other outcomes (5.2) in Section 5. We finish with Lessons Learned and Implementation Recommendations in Section 6.

4 Course Implementation and Assessment Approach

This section gives a brief overview of each course activity (Table 1) and which Course-specific Learning Outcomes and NAGT Outcomes are at least partially addressed. Table 2 is an example of the type of rubric used in grading simple student assignment answers, such as in daily assignments, with discretion used to assign percentages within these ranges. Most questions also had points-possible indicated so that students could gauge their relative significance towards the grade. Multi-component rubrics were used for more in-depth exercises, such as unit reports. In such cases, students were informed of the weighted percent for each section (e.g., title, abstract, introduction, etc.) and also given a detailed description of what should be included in each (https://d32ogoqmya1dw8.cloudfront.net/files/NAGTWorkshops/online_field/courses/sfm_feasibility_report.v2.docx). The same simple rubric (Table 2) was used to assess each weighted section. For example, the Discussion section was weighted 20 % and students were instructed:

"Here, you can discuss both pros and cons of the methods (What worked? Didn't work? What would improve the workflow?) as well as what you discovered about the Poudre River at the site. Return to the question of feasibility. Consider the overall goal of using SfM to assess geomorphic processes on the Poudre River at Sheep Draw. How could SfM be applied? What are the limitations?"

Similarly detailed instructions accompanied all components for the more in-depth exercises.

Table 2 - Example rubric showing percentage scoring used to assess course activities.

	Exemplary (75-100% points)	Basic (50-75% points)	Minimal effort (25-50%)	Nonperformance (0-25%)

General Considerations	Exemplary work will not just answer all components of the given question but also answer correctly, completely, and thoughtfully. Attention to detail, as well as answers that are logical and make sense, is an important piece of this.	Basic work may answer all components of the given question, but answers are incorrect, ill-considered, or difficult to interpret given the context of the question. Basic work may also be missing components of a given question.	Minimal performance occurs when student answers simply do not make sense and are incorrect.	Nonperformance occurs when students are missing large portions of the assignment.

4.1 Day 1: Getting started with Structure from Motion (SfM) photogrammetry

Course Unit 1: SfM and GPS/GNSS started out on Day 1 with an introduction to the SfM method. The day's activities were the first step in addressing Course Outcomes A (survey design) and C (point cloud data). After an overview presentation students used smartphone cameras to take ~20 overlapping photos of an object of interest (ex. sofa, shed, berm). For simplicity and to learn about local reference frames (rather than global ones from GNSS) they took compass bearing, inclination, and distance measurements and used trigonometry to calculate X-Y-Z coordinates for the ground control points (GCP). Students used Agisoft MetaShape software to post-process their photos and create the 3D point clouds. The software was available on their personal computers through a 30-day trial licence. Students then evaluated the performance of their model by considering data quality in different model regions and what method changes might improve their product. They also made recommendations for how SfM could be applied to different fields in the geosciences. The assessment of student learning was based on successful production of a locally-referenced point cloud and the data quality analysis.

4.2 Day 2: Introduction to GPS/GNSS

In the Day 1 activity, students used a relative local coordinate system to produce an accurately-scaled model. However, for real-world applications a global coordinate system is frequently preferable, which can be achieved with survey-grade

GPS/GNSS; so Day 2 was focused on Course Outcomes A (survey design), B (GNSS and geodetic survey), and E (justifying techniques). Day 2 morning activities were adapted from the GETSI module *High Precision* ~~Positions~~*Positioning* with Static *and Kinematic GPS/GNSS* ~~for use in ground control points for the associated SfM activity (Day 3). The UNAVCO-UNC team set up a base station receiver over an unknown point (Figure 3). The associated assignment has students use GNSS high~~. First students learned about the method through a lecture. Next they worked with data collected using different types of receivers and resulting accuracy and precision ~~point postprocessing methods to establish a base station used to establish a control point for a kinematic survey (establishing ground control points used in SfM activity on Day 3).~~. Assessment included a concept sketch of GPS/GNSS systems, quantification and evaluation of accuracy and precision of different grades of GNSS, and recommendations for appropriate applications of each.

In the afternoon of Day 2, students were introduced to the field site and methods used for data collection at the Cache la Poudre field location ~~——~~ (described above in Section 2). Students watched a video (Video 1; https://youtu.be/EZ5I8Ge8YjI) ~~introducing~~about the field site and ~~then~~ a video introducing the GNSS methods (Video 2; https://youtu.be/Xpj1QJf8AkY). Then, using the pre-collected base-station data, students ~~complete as~~completed the assignment ~~postprocessing for the static position, through the activity~~ "*Post-Processing GPS/GNSS Base Station Position*" ~~https://serc.carleton.edu/NAGTWorkshops/online_field/activities/239147.html.~~. Students ~~submit~~submitted the base station file to the Online Positioning User Service (OPUS), the National Geodetic Survey (NGS)–operated system for baseline processing of ~~standardized~~standardised RINEX files into fixed (static) positions. ~~Students interpret~~For the ~~output in~~assessment, students wrote a ~~relevant coordinate system and state~~paragraph explaining their procedure, interpreting the ~~errors associated with~~results, describing the ~~position. On Day 3, students use kinematic positions for the SfM ground control network~~difference between ellipsoid height and orthometric height, and ~~in SfM post-processing.~~highlighting anything that was surprising or confusing about the results.

~~2~~4.3 Day 3: ~~Kinematic GNSS Survey~~ SfM of Poudre River at Sheep Draw Reach

On Day 3 students combined skills learned in the previous two day in order to create a georeferenced point cloud from the field site (Course Outcomes A-C) and started to consider relevant geomorphic analyses (Outcome D). The morning exercise was *Ground Control **Points** and SfM at Cache la Poudre Site*

~~2.3.1 Kinematic GNSS Ground Control for SfM~~

~~To substitute students having hands-on training setting up the GNSS base station kinematic rover and collecting ground control points in the field, data were pre-collected by setting up a Septentrio receiver over a known base station (established during Post-processing GPS/GNSS Base Station Location exercise; Day 2; https://serc.carleton.edu/NAGTWorkshops/online_field/activities/239147.html) and Real Time Kinematic positions collected over ground control targets. Since this exercise followed one that introduced SfM and GPS/GNSS methods and students were~~

~~previously introduced to the site and methods with videos shot during data collection, students started~~. This began with a group discussion on where ground control points at the site should be placed ~~for their~~within the field area ~~of interest (Area 1 or Area 2;~~ (Figure ~~3~~1). Students ~~are~~were then given a text file of the x, y, z coordinates (UTM) collected by the UNAVCO-UNC team, and ~~must~~had to import them into ArcGIS to create a ground control ~~point~~ map. ~~A~~In a follow-up discussion ~~had~~, students ~~discuss the results of their map~~ compared ~~to~~the ground control point locations actually used in the prepared data with the locations they discussed for placement in the initial discussion. They were asked to ~~summarize~~summarise the strengths and weaknesses of the implemented ground control ~~point~~ plan at the site~~. This allowed them~~, which helped to ~~meet the student~~assess learning ~~outcome: "Develop an argument that is consistent with available evidence and uncertainty" as well as meeting those~~ related to ~~field and spatial relationships and communicate with written, verbal, and visual media.~~ both survey design outcomes.

~~2.3.2 SfM of Cache la Poudre River at Sheep Draw Reach~~

~~The authors had collected drone imagery of the Cache la Poudre site, for use in the Cache la Poudre SfM activity (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/239350.html; https://doi.org/10.5069/G9416V78). Images were acquired using a DJI Mavic 2 Pro drone. Two flight paths were flown at altitudes of 40-m and 50-m and different grid orientations with >70% overlap of adjacent photos with Pix4D capture. Before completing the SfM activity in MetaShape, students~~ The afternoon exercise was *Structure from Motion for Analysis of River Characteristics*. Students picked either Area of Interest 1 or 2 for their SfM workflow (Figure 1). Students with adequate computing power could choose to do the entire study region. Using resolution and height information about the UAS-collect photographs, students first calculated the expected resolution of the final point cloud ~~resulting from the SfM workflow. Students~~. They were then asked to assess what types of features or ~~process on~~processes at the Cache la Poudre study area they ~~expect can~~expected could be resolved ~~with this resolution. They were asked what~~; from there, they discussed the types of geomorphic questions they ~~can~~could feasibly expect ~~to~~ answer with the dataset ~~they will built~~.

~~Students picked either Area of Interest 1 or 2 for their SfM workflow (students with appropriate computing power can do the entire study area if they so choose). Students followed a~~of that resolution. Next students followed a more detailed Agisoft MetaShape Guide to construct a georeferenced point cloud of their Area of Interest. ~~Since students have already completed a~~As they were familiar with MetaShape ~~SfM model on~~from Day 1, ~~they~~students were able to work through the procedure independently. Once their model was complete ~~(example Figure 5),~~, students were asked to answer a series of questions related to error analysis of their model ~~(Figure 6)~~ and to reassess appropriate geomorphic applications~~. Students were also asked to reflect once again on~~ and design of the ground control ~~point~~ network used ~~(2.3.1).~~. Finally, students were asked to formulate a testable hypothesis related to processes on the Cache la Poudre River that they could answer with their dataset. For example, students ~~investigated~~could investigate cutbank stable bank heights and angles. ~~The activity described next allowed students to test their hypothesis and meet the first four NAGT capstone outcomes: 1) design and collect data to answer~~

~~a geologic question; 2) collect data on field relationships and 3) synthesize spatially to 4) interpret a process using multiple lines of spatially distributed evidence.~~ The completed exercise was the summative assessment and particularly revealed student accomplishment of SfM point cloud creation and geomorphic analysis.

2~~4~~.4 Day 4: ~~Working with Point Clouds and Building Rasters~~

~~2.4.1~~ Using CloudCompare and Classifying with CANUPO

On Day 4, students used the open-source software CloudCompare ~~(http://www.danielgm.net/cc/) that~~ (http://www.danielgm.net/cc/), which allows for viewing and manipulation of point clouds. This was a continuation of the same learning outcomes as Day 3 afternoon (Outcomes C and D) and continued on to some justification of methods (Outcome E). Students learned the basic operations ~~and use~~used in CloudCompare, ~~and~~ such as importing point clouds, classifying the points, and taking measurements that allow for hypothesis testing. They also ~~use~~incorporated an open-source plugin called CANUPO (http://nicolas.brodu.net/en/recherche/canupo/) that ~~allows for~~facilitates additional point cloud classification (Brodu and Lague, 2012)~~. Students learned to import point clouds into CloudCompare, classify the cloud, and took measurements on the cloud that allowed for hypothesis testing (formulated in 2.3). Students used the three dimensional point cloud to take measurements to test their hypotheses. Finally, students classified their cloud into~~, such as distinguishing between vegetation and ground. ~~They compared this classification with the MetaShape classification. Students~~ Students create a ~~raster~~digital elevation model (DEM) from ground points and export it for use in ESRI ArcGIS Map ~~(2.4.2).~~

~~2.4.2 Introduction to Rasters in~~. In ArcGIS

~~Students learned to import rasters in ESRI ArcGIS Map following the assignment "Working with Rasters in ArcGIS", within the Day 4 activity (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/240357.html). After importing the raster~~, students familiarized themselves with viewing ~~three-dimensional~~3D data in 2.~~5 dimensions. To aid in viewing, students~~5D and created hillshade and slope maps. ~~Students~~Then they were asked to retest their hypothesis with tools available in ArcGIS and 2.~~5 dimensions~~5D (e.g. measure tool, raster values). Students compared and contrasted applications with the three-dimensional point cloud versus 2.~~5-dimensional~~5D raster and ~~summarized~~summarised the appropriate uses and applications of each. ~~in the day's assignment.~~

2~~4~~.5 ~~Days~~Day 5: SfM Feasibility Report Assignment

The summative assessment for Course Unit 1 was the *SfM Feasibility Report*, which included assessment of all five Course Outcomes. Students were to imagine themselves as natural resource managers and ~~6~~

assigned the task of investigating the feasibility of using SfM to study geomorphic processes on the Cache la Poudre River. They were asked to summarize the SfM workflow and present the outcomes, limitations, and suggested applications of their

SfM model of their Poudre Area of Interest. On Day 5, students were given a work day to complete: "Unit 1: SfM Feasibility Report" (https://d32ogoqmya1dw8.cloudfront.net/files/NAGTWorkshops/online_field/courses/sfm_feasibility_ the report.v2.docx).

4.6 Day 6: Optional Field Trip

Day 6 consisted of an optional field demo wherebydemonstration during which students completed a GNSS ground control survey and Bywater-Reyes and colleagues collected droneUAS images at the Poudre Learning Center (https://youtu.be/s5CGhk8GIOU; Bywater-Reyes, Sharon: Poudre Learning Center Project. https://doi.org/10.5446/54388). This provided an additional Cache la Poudre dataset students were able to use in their final reports (section 2.7). These reports allowed students to practice the NAGT outcome to "Communicate clearly using written, verbal, and/or visual media (e.g., maps, cross-sections, reports) with discipline-specific terminology appropriate to your audience." The evaluation focused on whether students followed scientific report formatting.

2.64.7 Day 7: Introduction to Terrestrial Laser Scanning (TLS)

ThisDay 7 was the start of *Course Unit 2: TLS, Topographic Differencing, and Method Comparison* and began with an introduction to TLS methodology through a video and lecture. The exercise used pre-collected Terrestrial Laser Scanning (TLS; Bywater-Reyes, Poudre River at Sheep Draw (U-076); https://doi.org/10.7283/pstn-7r45)TLS data wherebythat the students were asked to compare and contrast this dataset with the previously created SfM dataset,point cloud they had developed in Unit 1, which was collected forfrom the same geographic location (Cache la Poudre River) on the same day (Figure 7). Students were introduced to the TLS methodology through a video and lecture (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/241028.html).3). The learning outcomes primarily focused on Outcome C (point clouds) but also laid the groundwork for more advanced method comparison to come (Outcome E). Students visually inspected the datasets for similarities and differences. As with the SfM activity, students; then they measured geomorphic features in the scene and comparecompared their measurements for the two methods. Using skills gained in previous class activities, students classified the TLS cloud into vegetation and ground, exported the ground cloud as a text file, and createcreated a raster that matched the specifications of the one made in the SfM activity (2.4.1).. This allowed students to complete differencing in three dimensionsprepared for 3D (cloud-to-cloud differencing) as well asand raster differencing in Day 8. Assessment (mostly formative) was based on their completion of measurements and a discussion of methods comparison, including a group discussion.

~~2.7~~**4.8** Day 8: Point Cloud/Raster Differencing and Change Detection

~~**2.7.1 Point Cloud and Raster Change Detection**~~

On the morning of Day 8 students used the concepts of point cloud and raster differencing to further compare their SfM and TLS results and interpret differences between the methods ~~used for high-resolution topography collection (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/241083.html).~~(Outcomes C and E). After ~~being given~~ a lecture ~~"Point Cloud Differencing", students conducted a~~ on point cloud differencing, students proceeded with differencing of the SfM and TLS data for their area of interest ~~on the Cache la Poudre River~~ using CloudCompare ~~(https://www.cloudcompare.org/doc/wiki/index.php?title=Distances_Computation) using~~with the M3C2 Plugin (Lague et al., 2012). Since these datasets were collected at the same place on the same day, differences between the datasets ~~should be interpreted as error~~were due to errors or uncertainties in one or both of the models. Students were asked to interpret the 3D differences between the datasets. The second lecture, ~~"Raster Differencing" discusses~~on raster differencing, discussed best practices in preparing rasters for ~~differencing. Students then used ArcGIS Raster Calculator tool to subtract one raster from the other (from same area of interest as the point cloud portion) making sure to use practices in raster creation and~~ differencing (Wheaton et al., 2010). Students ~~interpreted~~then used ArcGIS Raster Calculator tool to subtract one raster from the other. Students interpreted the results and compared ~~their~~the differences ~~conducted in~~between 3D (point cloud ~~differencing~~), and 2.5D (raster) differencing~~). Students~~. The summative assessment was the assignment in which students interpreted their results as an error analysis and ~~discuss~~discussed which dataset they think is more accurate (and why) and which method provided the most robust error analysis~~, practicing the associated NAGT capstone learning outcome (select data to answer a geologic question, collect accurate data, synthesize spatial and temporal data, develop argument consisten with evidence and uncertainty), with more rigor than in 2.4.2.~~.

~~**2.7.2 Raster Geomorphic Change Detection**~~

~~Here, students used pre-existing LiDAR datasets to conduct a Digital Elevation Model (DEM) of Difference (DoD). It also served to introduce students to additional high resolution topographic data (e.g., airborne lidar). In this assignment (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/241138.html), the students used~~So that the students could gain experience with airborne lidar data and with actual geomorphic change detection, during Day 8 afternoon they were given two lidar-derived raster datasets collected before and after the 2013 floods of the Colorado Front Range on a river (South St. Vrain Creek) that experienced substantial geomorphic change. ~~As such,~~In the exercise *DEM of Difference* students ~~practiced their~~practised raster differencing skills in the context of geomorphic change detection ~~(GCD)~~ and also ~~characterized~~characterised their detection limit with a simple thresholding approach. This ~~allowed~~helped to further address Outcomes C and D as students ~~to focus on temporal spatial data — enhancing their skills related~~answered questions in the

assignment about the differencing method and made a series of calculations that pertained to ~~NAGT's fourth learning outcomes.~~ geomorphic change.

~~2.8~~4.9 Day 9: ~~Airborne LiDAR~~OpenTopography Data Sources and Topographic Differencing

To broaden student knowledge of available data availability, Day 9 focused on additional **high resolution (usually lidar) data sources**

~~Following the in-depth exploration of two different high-resolution topographic methods (SfM and TLS) collected at the Cache la Poudre River site, Day 9 (https://serc.carleton.edu/NAGTWorkshops/online_field/activities/241410.html) focused on airborne LiDAR and additional data sources (e.g., OpenTopography).~~ After a lecture, students conducted an assignment using existing high-resolution datasets housed within OpenTopography (OT; https://opentopography.org/). First, ~~student practiced~~students practised downloading and viewing data from OT; second students conducted a topographic differencing exercise (Crosby et al., 2011), complementing the point cloud and raster differencing students conducted in Day 8 ~~(section 2.6) of the course. On~~. As with Day ~~10 of~~8 afternoon, the learning outcomes primarily focused on point clouds and geomorphic analysis (C and D). The learning assessment was done via the ~~course,~~student assignment, in which students ~~finished their~~determine erosion and deposition in a dune field and analyse error and detection thresholds.

4.10 Days 10 and 11: Methods Comparison Report and Presentation

The summative assessment for Course Unit 2 and the course as a whole was the final ~~report: "Unit 2: Using High Resolution Topography to Address Societal Problems" and presented their final projects in Day 11.~~ *Methods Comparison Report* and presentations in the last two days of the course. Students picked from a variety of options including: improving methods from Unit 1 (SfM and TLS methods), adding new elements to Unit 1, choosing an additional exploration with the datasets collected on the optional field day, or using a different dataset such as airborne ~~LiDAR. One student downloaded airborne LiDAR for the Cache la Poudre River and compared SfM, TLS, and airborne LiDAR for the same area! The final report allowed students to learn from their previous report and Unit 1 performance and practice the NAGT outcome to "Communicate clearly using written, verbal, and/or visual media (e.g., maps, cross-sections, reports) with discipline-specific terminology appropriate to your audience" as well as "Work effectively independently and collaboratively (e.g., commitment, reliability, leadership, open for advice, channels of communication, supportive, inclusive)." Students were evaluated both on their execution of scientific report writing as well as the scientific method and hypothesis testing.~~ lidar. As the course summative assessment the report pulled together student learning on all five course outcomes. The presentation (Day 11) additionally gave students practice in oral presentation of scientific findings.

5 Results

5.1 Course-specific learning outcomes

This section provides a variety of examples of how students met the different course-specific learning outcomes. It is not intended to be exhaustive but to provide general illustrations of student learning drawn from both assignments and Slack daily reflections and discussions.

5.1.1 A) Make necessary calculations to determine the optimal survey parameters and survey design based on site conditions and available time

In the GNSS/GPS accuracy and precision activity (Day 2), students showed their ability to evaluate appropriate GPS/GNSS techniques in different contexts with the GPS/GNSS error analysis activity (Day 2). Students calculated and compared accuracy and precision of different GNSS/GPS methods and (Day 2) explained which types of surveys or research applications are appropriate for each. Students received an average of an 89 % of this assignment (exemplary), evidence of their ability to link calculations to applications. Students also completed a concept sketch of GNSS systems (Figure 4) describing what factors can interfere with GNSS performance.

In the SfM activity (Day 3), students calculated the pixel resolution resulting from the flight parameters used in the pre-collected UAS images and assessed the appropriateness of this resolution to resolve features within the flight. One student wrote in their assignment, "*Obviously the larger scale features will be resolved, like the eroded bank, point bar, and the sidewalk panels in the river, as well as most sizes of vegetation. If the sampling is 0.3-0.5 centimetres per pixel, then it should be able to resolve grasses, and just about any size of gravel. The difference between the water surface and adjacent should be pretty well resolved as well.*" They were also given the UAS flight time for the survey. Thus, students could easily adapt this approach to calculate the time it would take to accomplish a flight reaching the desired resolution for a given application. The discussion of implementation of ground control at the field site (Day 3) allowed students to compare the actual implementation with literature-recommended protocols to discuss strengths and weaknesses given the site conditions (Figure 5). Students also showed the ability to discern improvements to the survey plan given the site condition. For example, one student wrote: "*I think the GCPs* [Ground Control Points] *are very well placed in area-1 and area-2. But the adjoining area of both the areas only got two GCPs- GC4 and GC10 which is too [few]. It may reduce the accuracy of map while joining area-1 and area-2. In addition, area-2 has only one GCP in North direction which may become an issue during georeferencing. To be on safer side we may include one more GCP near GC9 to ensure the coverage of area-2. If only 9 GCPs are available to me then I think the current arrangement of GCP is best*." Students received an average of 98 % (exemplary) on this discussion, highlighting their ability to evaluate appropriate methods given site conditions.

5.1.2 B) Integrate GNSS targets with ground-based lidar and SfM workflows to conduct a geodetic survey

Students used pre-collected GNSS-measured ground control points to georeference the resulting SfM point cloud in the Day 3 SfM activity. As described in the previous section (5.1.1), students integrated the GNSS data into the SfM projects and also discussed the overall survey design and resulting model errors. The suite of activities that used pre-collected GNSS data was successful as indicated by assessment data and student discussions (5.1.1). Whereas students did integrate GNSS targets with an SfM workflow to conduct a geodetic survey, they did not actively integrate GNSS targets for the TLS workflow. The lack of TLS-target integration stemmed from the remote nature of the course and pre-collected nature of the field campaign whereas an in-person implementation would have allowed students to be actively involved with TLS target GNSS data collection and integration. Future remote implementations would need an activity that involves students in TLS GNSS targets data collection and post-processing to meet this learning outcome. However, given the complicated nature of TLS data post-processing, the authors recommend a simple activity such as a discussion of recommended scan locations and a comparison of actual GNSS target locations compared to the recommendation (e.g., similar to that conducted for the SfM field project). In a virtual course format, this learning outcome would need to be edited in the future.

5.1.3 C) Process raw point cloud data and transform a point cloud into a digital elevation model (DEM)

Students practised and successfully converted raw point clouds to DEM's several times (Day 4 and Day 7), and also learned how to use the native MetaShape point cloud classification (Day 3) as well as the open-source CANUPO (Day 4) version. When comparing point cloud versus raster elevation products, a student wrote:*"It was hypothesized that SfM methodologies would be best at providing measurements of large-scale elevation changes, however the clear decrease in point cloud density decreased our confidence in these large-scale elevation change measurements along the bank. Small-scale elevation changes along the point bar were best represented by the ArcMap generated hillshade map and DEM while large-scale elevation changes were best represented by the ArcMap generated slope map and DEM. The slope map also had the unique feature of highlighting areas of constant slope and could be used to distinguish between manmade structures and natural vegetation areas in a site of flood damage."* Here, the student showed their ability to recognize pros and cons of point cloud versus raster (DEM) products. Students received an average of 84 % (exemplary) on the raster derivation and manipulation assignment and did even better when they repeated this process. Students received an average of 89 % (exemplary) on the TLS assignment, where they were asked to repeat the process of conducting a quantitative analysis on the cloud, classify the point cloud, extract ground points, and create a DEM, showing their ability to repeat a workflow originally implemented over several days in one step independently to produce a DEM.

5.1.4 D) Conduct an appropriate geomorphic analysis, such as geomorphic change detection

With the SfM and TLS field datasets, students recognized the limitation of having only one time snap. A student reported:

"Structure from Motion to assess geomorphic processes on the Poudre River at Sheep Draw is useful and easy to operate. In this project we used SfM to create a model that can measure bank erosion and deposition. However, we did not have enough information to analyse the rate at which the river was eroding the bank. To conduct this study we would need to conduct several SfM surveys over a length of time to acquire enough variance in data to calculate a rate." This statement illustrates the student's recognition of the utility of repeat topographic data needed to conduct a geomorphic change analysis that would be appropriate to answer a geomorphic question they had posed.

In the context of comparing SfM and TLS data collected at the field site at the same time, students conducted point cloud and raster differencing (Day 8). Students received an average score of 78 % (low-end of exemplary) on this assignment and extrapolated how one could apply these methods to geomorphic change detection. A student noted in their daily Slack discussion, *"Learning about DoD [DEM of Difference] was a little confusing to me and some of the assignment parts threw me off but other than that I felt like I learned good things today!"* Another that: *"Today's work was a lot more confusing than the last couple days, but it's much more satisfying."* Students illustrated their enthusiasm for manipulated point clouds. A student wrote in their daily discussion, *"Today I enjoyed getting visible products using ArcMap and Cloud Compare."* In comparing the SfM and TLS datasets, a student demonstrated their understanding of how the differencing would be used in the context of geomorphic change by stating: *"During geomorphological analysis, magnitude and direction are both important. Areas that are positive show deposition, while negative areas show erosion."*

Students conducted lidar geomorphic change detection with the Day 8 afternoon activity using regional LiDAR from Colorado 2013 floods and Day 9 (OpenTopography change detection). Students received the lowest assignment scores on these, with 50 % and 75 %, respectively (basic to minimal performance level). This may indicate a combination of confusion and burnout two-thirds of the way through the intensive two-week course. 35 % and 17 % of assignments, respectively, were assigned a 0 % because submissions were missing. If only submitted assignments are considered, average scores are much higher (76 % and 92 %, respectively), indicating those who were able to stay on top of the dense course format were able to perform geomorphic change detection to an exemplary level. Students' scores on the Unit 2 report, which combined elements from the entire course, support the notion that students may have been fatigued and prioritising assignments worth more points. Average Report 2 scores were the same as Report 1 scores (76 %). One student even went so far as to download airborne lidar for the Cache la Poudre River and compare SfM, TLS, and airborne lidar for the same area, showing their ability to combine skill taught in the course and use DEM differencing analysis for either error or geomorphic change detection, depending on the context.

5.1.5 E) Justify which survey tools and techniques are most appropriate for a scientific question

The progression from the introductory SfM project (Day 1) to a field-scale SfM and TLS comparison (Report 2) allowed students to assess limitations and justify appropriateness of survey techniques to different applications and scientific questions. Students highlighted where their intro SfM projects (Day 1) produced accurate point clouds and under which conditions the

point clouds had missing data or high error (Figure 6). They were asked to reflect on field applications appropriate for a model of a similar quality. In the field SfM (Day 3) and TLS (Day 7) activities, students explained where the three dimensional models had adequate coverage for different applications.

For the SfM field assignment (Day 3), students considered model errors (Figure 7) and classification performance in their assessment of appropriateness for scientific questions. Students received an average of 88 % on the SfM field assignment (exemplary work), which asked them to think about the questions they set out to answer and discuss whether this would be possible given the errors and limitations of the model. A student noted:

"*Given the limitations of the model, I'm not sure if I'll be able to answer the question about the vegetation, and I may be able to work on the erosion, but I'm not sure. There are three questions I would like to answer:*

1. *Can we identify a flood plain in the area?*
2. *Is the erosion on the bank from normal flow, or the 2013 flooding?*
3. *Can we determine the erosion rate on the banks?*

I believe at least the third question can be quantifiable, but the other two might also be quantifiable. The flood plain may be calculated, but a larger image may be needed. The erosion may also be quantifiable. Erosion rate is most likely measurable because we can use the sand bar on the other side of the river as a measure of erosion. Some larger images, and some more up-close images of the bank may be needed to answer these questions."

Several students observed the limitations of SfM in the presence of vegetation: A student observed: "*Pros of using SFM method is that it can create high resolution data sets at relatively low costs. A negative aspect about this method is that it cannot generate any data through vegetation and so the environment this method can be used in is limited.*" Another student noted: "*Unlike LiDAR technology which is able to image past vegetation and "see" the ground, SfM images cannot see through foliage. While multiple angles of a site can help create ground points beneath vegetation, thick foliage will always have to be removed from the dataset if one is trying to use SfM to create a Digital Elevation Model rather than a Digital Surface Model. Erroneous points below the surface of the water also were prevalent in the 3D point cloud and needed to be removed.*" An additional student observation was: "*It would be useful to conduct a study in the summer and winter every year to analyze the change in bank height and distance from the river to the walking path. This method can be done with SfM, but it would be best to use several types of surveying methods to create an accurate set of data because SfM lacks the ability to see beneath trees, vegetation, and the undercut bank due to the drone being 40 to 50 meters in the air. Therefore, terrestrial and airborne lidar should be used to image the areas where SfM lacks.*" When comparing SfM and TLS (Day 7) a student noted in their daily Slack discussion post, "*I was surprised at the difference in quality between the SfM and TLS. I would think TLS would have much higher quality data but perhaps this site was not a prime example of its capabilities.*" These observations show students understood the limitations and appropriateness of SfM and TLS surveying and also show the ability to improve upon future acquisitions through editing the data collection protocol.

5.2 Other course outcomes

5.2.1 NAGT outcomes

This course operated under difficult conditions (e.g., global pandemic), but allowed students to meet degree requirements and accomplish course-specific learning outcomes in addition to meeting many of the capstone field experience student learning outcomes developed by the field teaching community in collaboration with NAGT (Section 2.3; Table 1). Assessing whether each NAGT outcome was met is beyond the scope of this manuscript, however, a few that were especially well addressed, and also those that were not, are highlighted here.

NAGT Outcomes 1-5 were practised in many assignments and were highly aligned with course-specific outcomes (Table 1). Students did not specifically design a field strategy in its entirety (NAGT Outcome 1), but they did assess the strengths and weaknesses of field strategies and recommend improvements in order to answer a geologic question. This was, for example, met along with course-specific Outcomes A and B (see Sections 5.1.1 and 5.1.2). They additionally collected data that allowed them to assess field relationships and record those with both 2D conventional maps (NAGT Outcome 2) as well as with 3D representations, well-represented by course-specific Outcome C (see Section 5.1.3). A related outcome (NAGT Outcome 6), communicating these products through written products was accomplished through all daily assignments in addition to the two written reports. Verbal communication was accomplished through group discussions as well as group oral presentations at the end of the course, which also aligned with NAGT Outcome 7 (working in a collaborative team). Students synthesised data, integrating information spatially and temporally, to test hypotheses concerning the past/current/future conditions of an earth system using multiple lines of spatially distributed evidence (NAGT Outcomes 3 and 4). In particular, Course-specific Outcome D can be referenced for examples (see Section 5.1.4). Finally, students developed arguments consistent with available evidence and uncertainty (NAGT Outcomes 5) aligns with Course-specific Outcome E (see Section 5.1.5).

The NAGT outcomes that received less intentional attention were the last two: "NAGT Outcome 8: Reflect on personal strengths and challenges (e.g., in study design, safety, time management, independent and collaborative work)" and "NAGT Outcome 9: Demonstrate behaviors expected of professional geoscientists (e.g., time management, work preparation, collegiality, health and safety, ethics)." 3Students reflected on personal strengths and challenges (NAGT Outcome 8) and discussed time-management strategies in an informal way in their daily Slack discussion posts. Students wrote:

"I also struggled with the excel worksheet today. It started making more sense towards the end, I will definitely have to go back and rewatch the meetings to grasp everything that is going on. For the GNSS sketch assignment, I'm not exactly sure what exaclty this questions is asking if anyone could help, thank you!"

"Today's work was not as confusing as the past few days. Having background knowledge on ArcMap definitely helped, but Cloud Compare took a while to maneuver. Just trying to keep up with the assignments and get the readings done. I'm trying to make it out on Sunday, though! I think the in-person field component will be really cool, and seeing other human

beings would be awesome haha. As [student name] mentioned, interpreting the models can be tricky and applying them back to what we've been learning takes time, but really helps! Those connections do a great job to solidify the lessons."

"I think my biggest challenge today is interpreting all the models (DEM, hillshade, slope, etc) and what each one can be used for. I used USGS satellite images and classified them years ago in ArcMap for a project but I feel like I remember almost nothing from that so I'm a little lost!"

I'm still catching up from yesterday as well, but I feel significantly better than I did 24 hours ago! I remember just enough about ArcMap for it to be fun to figure out new challenges rather than frustrating, and I think that that was a nice boost after previous frustrations.

5.2.2 Demographic outcomes

The cancellation of many field courses and change to remote instruction culminated in a more diverse course than UNC Earth Science majors' typical demographic makeup. Students came from a wider variety of geographic regions, including six US states, one US territory, and one international location. Twenty-four percent of students (out of class of 23) were from historically minoritized groups (American Indian or Alaska Narive, Asian, Black or African American, Hispanic or LatinX, and Multiracial) and 56 % were female compared to the 2011-2020 UNC Earth Science majors' averages of 17 % and 39 %, respectively. Remote instruction may therefore aid in increasing representation in minoritized groups. At least 40 % of students needed the course to meet degree requirements and most of the seven graduate students needed the expertise for their graduate research.

6 Lessons Learned and Implementation Recommendations

Despite the challenging conditions under which this course was implemented, the course was highly successful overall by a number of metrics, including frequently exemplary-level accomplishment on assessments and nearly all students passing the course. When course-specific learning outcomes are considered, the vast majority were met, as indicated by assignment-specific outcomes (section 5.1) as well as by their self reflection from the Slack daily discussion. In particular, students were able to achieve Course-specific Outcomes A, C, D, and E (Section 2.3; Table 1) particularly well. Learning Outcome A (make necessary calculations to determine the optimal survey parameters and survey design based on site conditions and available time) was well-realised in terms of students' ability to understand the time it takes for post-processing and interpreting data of a variety of types, and how one might improve upon the workflow. However, students did not receive the hands-on experience they would have in the field. For example, they are not able to evaluate the time to set-up an RTK GNSS system, lay out ground control points, survey them in and fly a UAS over the area with an appropriate team. This allows one to know the spatial extent one can realistically cover in a given time. Students did learn the time it takes to post-process the imagery into an SfM model as well as derivative products (e.g., rasters). Students also did not accomplish a sense of the time required to

conduct a TLS survey. We realised in retrospect that Course Outcome B (Integrate GNSS targets with ground-based lidar and SfM workflows to conduct a geodetic survey) was not fully accomplishable in the remote setting. Students were able to propose and evaluate the design for ground control points in an SfM survey, but they were not able to actually "conduct" the survey. Nor was the course able to provide an opportunity for similar experience in a lidar survey. If the course is taught remotely in the future, this outcome should be rewritten to something more along the lines of "Recommend locations for a set of ground control points for an SfM and/or TLS survey and critique surveys designed by others." The current Outcome B would be appropriate for an in-person field course in its presented form.

The lowest level of accomplishment in the course came during the Day 8-9 assignments (5.1.4). As described, this is likely because of a combination of difficulty and burnout. This course was moved to virtual because of safety concerns surrounding COVID-19. However, the time commitment was kept the same as originally scheduled for in-person. As such, the course was about two weeks (for three credits) fulltime (all day plus homework), similar to what would be expected for a traditional in-person field-camp style course. This schedule proved exhausting with the online (Zoom lecture and office hours) commitments for the course (morning and afternoon) combined with the computer-intensive nature of the assignments. In particular, challenges in this format included 1) computational access (e.g., a good enough computer) and 2) access to ~~a~~the time and space needed to complete the course. Several students dropped the course when they ~~realized~~realised these constraints because of work and family obligations. ~~We recommend, if the course is adapted in its entirety~~However, of the 23 students who stayed enrolled in the course, 48 % received an A, 17 % a B, and 26 % a C, with A, B, or C marks comprising 91 % of the course. This demonstrates a high level of competence and performance for the vast majority of students. One student earned a D (corresponding to 60.0 % - 69.9 %) by completing 70 % of the assignments. This student expressed difficulty focusing for the length of time required for the course's pace. There was one student who earned an F which reflected participating and turning in only one day's worth of assignments. These students, while the minority (2 out of 23), should not be ignored. Studies suggest COVID exacerbated the ongoing mental health crisis among college students, increasing depression and anxiety (Son et al., 2020; Wang et al., 2020). The combination of COVID-19-related stress, virtual nature of the course, and intensity of workload likely contributed to feelings of anxiety in this course. We recommend, if this course is taught virtually in the future, to implement it as a longer interim session (minimum four weeks), quarter-, or semester-long course. Additionally, having computers available in a lab or on loan with the appropriate computational and software needs would be helpful. Students wrote in Slack reflections:

"The only struggle I am having is my computing capabilities and it always crashing."

"I had to keep my computer running last night to generate the dense point cloud, but am glad to see that this morning it has finally finished so that I can finish up the assignment.

"To improve the workflow when using this method in the future, a better computing device that can handle large files would be better"

If implemented as an intensive workshop, we recommend using at most four days' worth of material (as presented here (eg., most of Unit 1). Any individual ~~unit~~activity could be adapted as an assignment in an upper-division geomorphology or quantitative geoscience methods course. ~~Despite the challenging schedule, the diverse set of students in the course were successful, with 48 % of students receiving an A in the course, 17 % a B, and 26 % a C with the remaining 9 % (2 students) receiving D or F grades~~We are fairly certain that increasing the available time and support to complete the later assignments would mitigate the majority of the problem with lower student success, but we also suggest re-evaluating the later assignments for instructional clarity and supporting resources.

~~This course operated under difficult conditions (e.g., global pandemic), but allowed students to meet degree requirements and accomplish most of the end-of-capstone field experience student learning outcomes outlined by NAGT.~~
~~Specifically, students practiced spatial and temporal data collection and interpretation, study design, hypothesis testing, error analysis, presenting information in appropriate written, verbal, and visual formats, and working collaboratively. The outcomes that received little attention were the last two: "*Reflect on personal strengths and challenges (e.g. in study design, safety, time management, independent and collaborative work)" and "Demonstrate behaviors expected of professional geoscientists (e.g., time management, work preparation, collegiality, health and safety, ethics)."* In the remote setting, it was difficult to replicate the as-needed problem solving and decision making that often arises in the field, and the reflection that follows. These would need to be emulated in a more explicit way than was accomplished here. Regarding the course-level student learning outcomes, students certainly met them all. They are able to: 1) Make necessary calculations to determine the optimal survey parameters and survey design based on site and available time, 2) Integrate GNSS targets with ground-based LiDAR and SfM workflows to conduct a geodetic survey, 3) Process raw point cloud data and transform a point cloud into a digital elevation model (DEM), 4) Conduct an appropriate geomorphic analysis, such as geomorphic change detection, 5) Justify which survey tools and techniques are most appropriate for a scientific question. These skills are marketable in both research and the commercial workforce.~~

Lastly, student feedback and requests for additional offerings of the course indicate student appreciation of the course. One student wrote the instructor, "*I just wanted to thank you for the class. I have had an incredible journey during my university experience. Without this class being offered I truly do not know what I would have done. This has been a very trying time in my life and completing this course was the push I needed to continue through. I can't thank you enough for doing this. Not only offering the class but how flexible you were and understanding. Hands down one of the best professors I have had to date. You are an incredible teacher and I am very grateful that I took this class with you. Once again, from the bottom of my heart, thank you!*"

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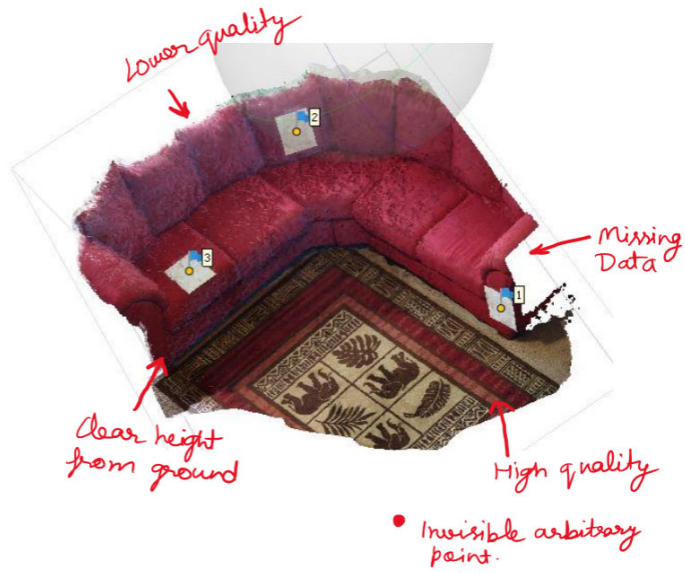
Figure 1: Student SfM product from Day 1 exercise where assessment (created by student in course; student not disclosed to comply with Institutional Review Board).

XYZ positional data transmitted to antenna

Usually four satellites communicate with time sent and recieved

Base Station Receiver
Fixed point allows for higher precision

Portable Receiver
Used in the field

Things like the weather and buildings can interfere with the communication

WORLD MAP

High grade systems can be used for very precise applications like tracking mm-scale tectonic movements

less precise consumer grade equipment communicate to satellites with less accuracy & precision like navigation

Figure 1.

~~Figure 2: Student sketch of how GNSS works, including disruptions and applications thereof (created by student in course; student not disclosed to comply with Institutional Review Board).~~

Figure 42. Base and Kinematic GNSS methods (left) and example of ground control (right) surveyed for use in GNSS and SfM activities.

Figure 5. Example of a student's area of interest (left) picked and associated MetaShape georeferenced point cloud (right) of their area of interest (created by student in course; student not disclosed to comply with Institutional Review Board).
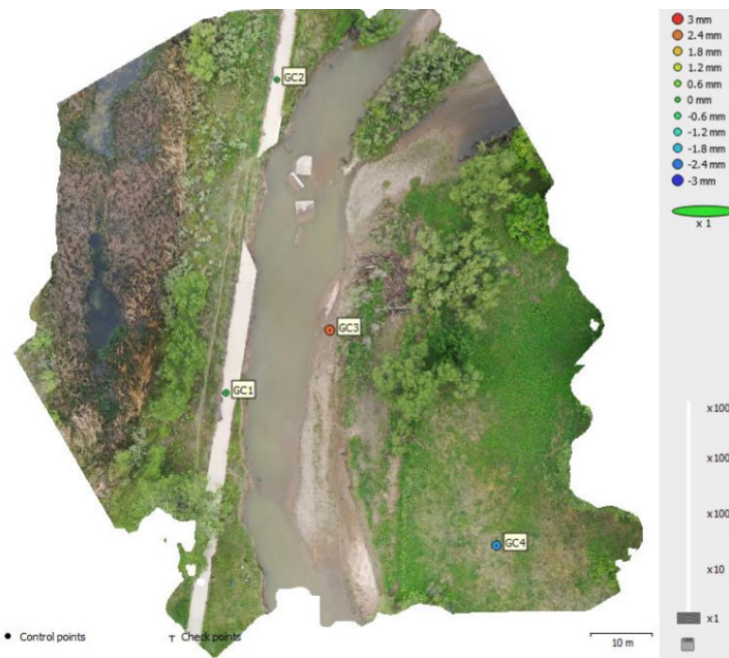
Figure 3.

~~Figure 6. Example area of interest showing error analysis (created by student in course; student not disclosed to comply with Institutional Review Board).~~

~~Figure 7.~~ **The top shows the Terrestrial Laser Scanner (TLS) photograph from a scan location whereas the bottom shows the associated point cloud at the Cache la Poudre River site. Courtesy UNAVCO.**
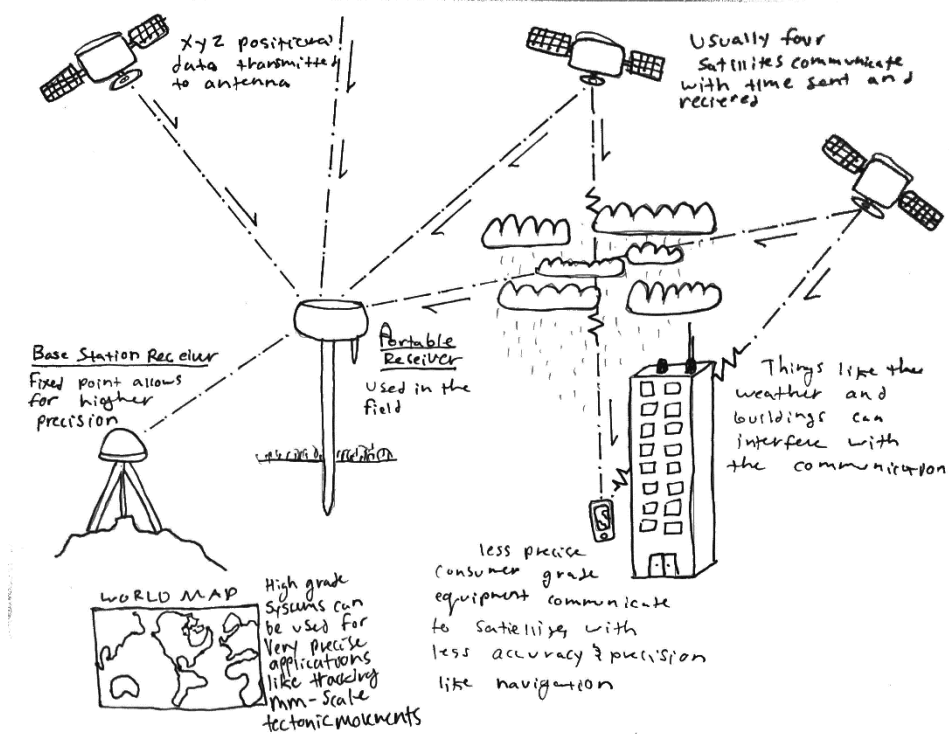
Figure 4: Student sketch of how GNSS works, including disruptions and applications thereof demonstrating theoretical understanding of GNSS (created by student in course for Day 2 activity; student not disclosed to comply with Institutional Review Board).

Sheep Draw Ground Control Points

My primary objections to GCP placement are that GC1 and GC2 are likely at very similar elevations and that GC5 and GC8 could stand to be farther apart. I personally think that the pattern of the ones placed around Area 2 is a bit boxy and could stand to be more staggered as well. However, overall I think that the GCP markers are placed in such a way that the most inhibitive vegetation is avoided and I appreciate that aspect.
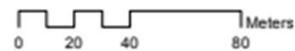
Figure 5. Student map of ground control points (GCPs) used in SfM activity (created by student in course; student not disclosed to comply with Institutional Review Board). Through a group discussion on Day 2, students discussed whether GCPs were adequately placed and suggested implementation improvements. Imagery source: ArcGIS® software by Esri.
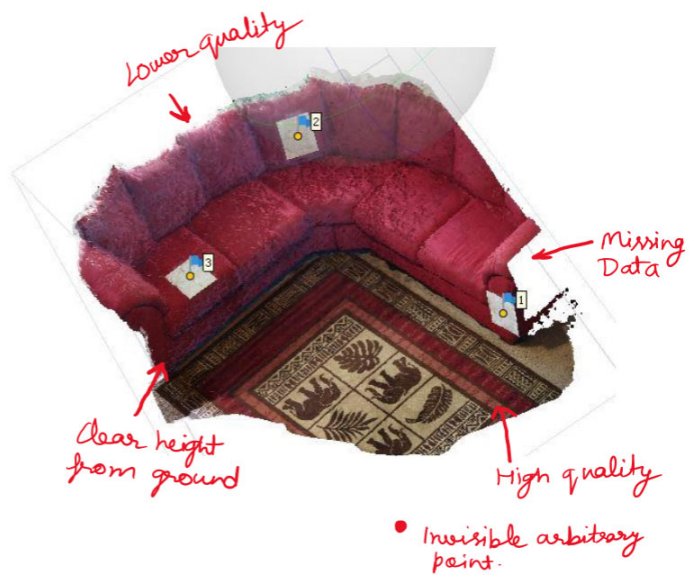
Figure 6: Student SfM product from Day 1 exercise (created by student in course; student not disclosed to comply with Institutional Review Board). Student successfully assessed relative data quality as indicated by student's markup, and where data was missing or of low quality.
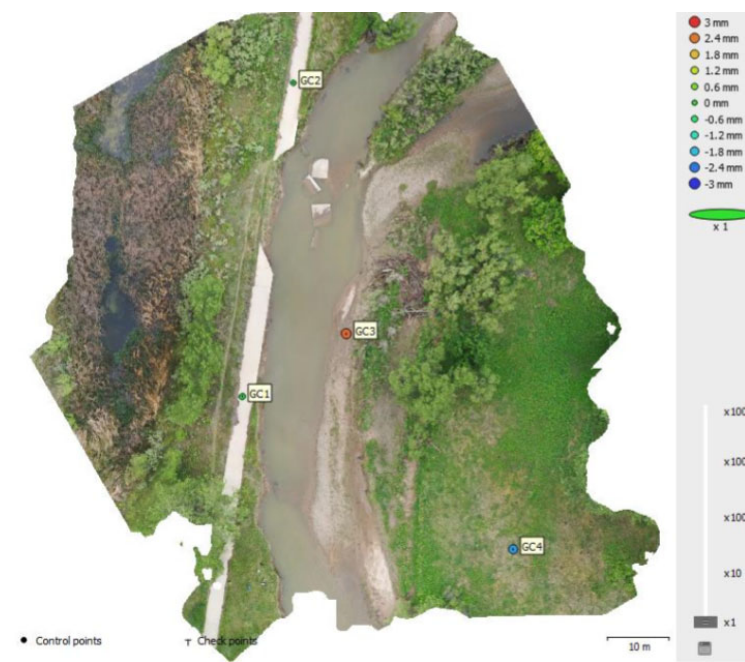
Figure 7. Student-generated colored SfM point cloud of their area of interest showing GCP error ellipsoids used by the student in their SfM error analysis (created by student in course; student not disclosed to comply with Institutional Review Board).